

# Soil–Geomorphology Relationships in the Pichiñán Uraniferous District, Central Region of Chubut Province, Argentina

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**Abstract** The aim of this work was to perform a baseline study about pedologic components of the geomorphic surfaces of different origins in a sector of the *Cerro Solo* uranium ore deposit, situated in the arid central region of the province of Chubut, Argentina. This contribution was requested by the National Atomic Energy Commission of Argentina (CNEA). The geomorphological units identified in the study area were: (1) Exhumed planation surfaces, composed of rounded hills of mesosiliceous-basic volcanic rocks of Middle Jurassic age; (2) Pedisediments, consisting of four Early Pleistocene alluvial terrace levels; (3) Pediment association levels carved on the continental Cretaceous sediments; (4) Alluvial fan relicts, with three geomorphic surfaces; (5) Modern alluvial fans, composed of two coalescent alluvial fans, and (6) Alluvial plains and associated wetlands (locally known as *mallines*). The latter are located in restricted areas where the water table is discharged at the thalweg sectors of the channels. The soil parent materials are free of carbonates (e.g., alluvial

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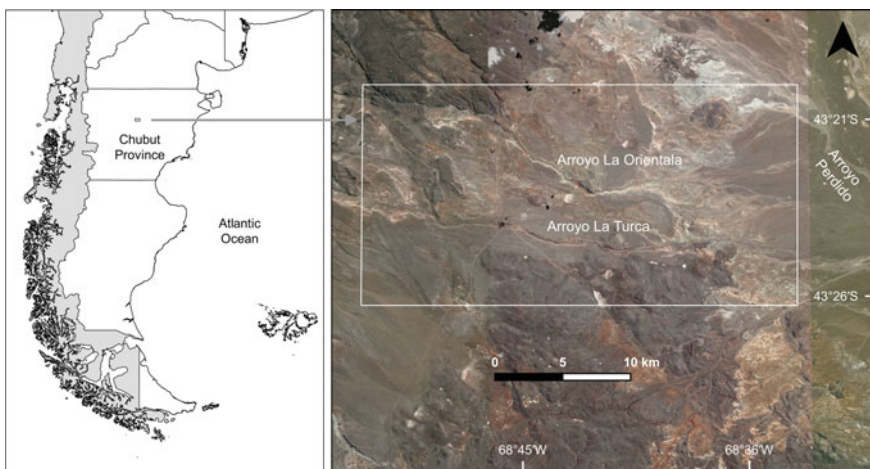
origin) and their origin could be allochthonous, mainly by aeolian influx. These soils were classified as Calcids soil suborder, and their differences are due to the different development degree of calcitization and polygenesis. The soils developed on pediments have a varied morphology and soil types depending on the age of geomorphic surface and the degree of polygenesis, this last resulting from the alternation of morphogenesis periods with pedogenic periods. The soils more developed were classified as Natrargids and Haplargids, whereas the oldest are truncated and were classified as Haplocalcids. The soils of the younger level were classified as Torriorthens. The soils formed on alluvial plains were classified as Torrifuvents.

**Keywords** Aridisols · Geomorphic surfaces · Exhumation planation surfaces · Pediment association · Pedisediment levels · Alluvial fans · Patagonia · Argentina

## 1 Introduction

The landscape of the Sierra de Pichiñán area (Fig. 1), as well as the Extra-Andean Patagonia region, is characterized by severe arid conditions. Low rainfall rate and sparse vegetation cover are typical features of arid regions and are of considerable importance for the operation and development of landforms (Thomas 1997).

Although wind is an important geomorphological agent that has deeply modified the arid region landscapes, water erosion due to short- and high-intensity rainfalls is the most intense geomorphic process in the Sierra de Pichiñán area, either as raindrop splash, surface runoff (interrill erosion) or as concentrated flow erosion, in the form of rills and badlands. Many of these landforms have large patches of bare soils (desert pavements and surface soil crusts) and thus they are exposed to wind erosion, raindrop impact, and surface runoff.



**Fig. 1** Study area of Sierra de Pichiñán

Also, the scarcity of available water seems to be the limiting factor not only for plants, but also for soil formation. Chemical weathering, clays formation, translocation of particles, and ionic solutions should not occur under these conditions, and only weakly developed Entisols (Soil Survey Staff 1999) should be in the region. However, strongly differentiated soil profiles appear in these areas. These could be explained if soils processes are related to relict features of colder or wetter climates of the past (Nettleton and Peterson 1983) or if they could be attributed to the seasonally marked extreme rainfall years occurring in the present thus producing deep leaching (Buol et al. 1990). In restricted areas strongly differentiated soil profiles could be also explained in response to local dominant factors that are independent of the effect of climate and vegetation (intrazonal soils). Examples of the last are hydromorphic soils of on wetlands locally named *mallines* (Aquets).

The soil–geomorphic research emphasizes the relation between soil properties, soil development, landscape form, and geomorphic processes. Olson (1989) considers that a research in soil–geomorphology requires three investigative aspects: (1) knowledge of the surficial stratigraphy, (2) the geomorphic surface defined in time and space (Rhue 1975), and (3) correlation of soil properties to landscape feature.

In this regard, studies on soil–geomorphology relationship have used geomorphic surface concept in the context related to soil age and landscape position (Gile et al. 1981). The geomorphic surface is a unit that may be mapped and which includes a number of landforms and landscapes. This surface may be erosional or constructional and is often a combination of both (Daniels et al. 1971).

In this framework, soil–geomorphology relationship will deepen topics of interest for use as: (1) Quaternary geology (soil chronosequences and paleosols), (2) geo-ecology (vegetation distribution patterns and soil–plant relationships), and (3) soil degradation.

The aim of this work was to perform a baseline study on pedologic components of geomorphic surfaces of different origins in a sector of the *Cerro Solo* uranium ore deposit, situated in the central region of the province of Chubut. This contribution was requested by the National Atomic Energy Commission of Argentina (CNEA).

## 1.1 Study Area

The study region (Fig. 1) covers an area of 267 km<sup>2</sup>, which is considered potentially susceptible of receiving the impacts of mining and covering the main geomorphological units of geo-ecological interest.

The oldest rocks that crop out are the Lonco Trapial Formation (Lesta and Ferello 1972) of Middle Jurassic age (Bajocian–Bathonian), composed of mesosiliceous-basic volcanic rocks, mainly lava flow facies accompanied by tuffaceous facies (Proserpio 1987). This volcanism precedes the Atlantic Ocean opening and corresponds to a wide extensional province covering a continental intraplate region (Aguilera et al. 2010). This geological unit crops out in the south-central and northeast of the study area.

Between these volcanic outcrops, an extended erosion landscape is developed. It is constituted by sedimentary rocks of fluvial and pyroclastic origin of the Chubut Group (Barremian–Santonian; Figari and García 1992). The Chubut Group is composed of the Los Adobes Formation (fluvial sediments; Early Albian) and the Cerro Barcino Formation (pyroclastic rocks; Aptian–Albian?). This latter is the geological unit with larger distribution in the area (Marveggio and Llorens 2013).

The continental Cretaceous rocks are buried by Pleistocene gravels and sandstone deposits, forming relict landforms both as plains with a plateau shape or alluvial piedmonts. This geological unit was assigned to the Renguenao Formation (Berizzo 1976) of Early Pleistocene age (Nullo 1983) and its genesis is related to pedisediments and old alluvial plains widely distributed in the area.

The climate of this area is cold and dry with an important annual oscillation. The rainfall is only 200 mm/a. January temperatures average is 19 °C, whereas on July the average is 3 °C. Absolute maximum and minimum are 38.3 and −24.2 °C, respectively (1981–1990 average, Servicio Meteorológico Nacional, SMN). The temperature and moisture regime for the relieved area are mesic and aridic, respectively (Beeskow et al. 1987).

## 1.2 Methodology

The geomorphic surfaces were defined by digitalization on screen from satellite images and aerial photographs analysis (1:60,000; Instituto Geográfico Nacional, [www.ign.gob.ar](http://www.ign.gob.ar)). Cartographic adjustments were performed by means of field control.

The present work follows a hierarchical classification adapted from Peterson (1981) that uses the geographic scales, genetic relationships and shapes of the topographic forms. A geomorphological unit is the landform defined by morphogenetic criteria such as relict landforms. Relict landforms comprise remaining parts of a same geomorphic surface which has been otherwise degraded by erosion. An erosional relict must be older than the destructive erosion cycle. Recognition of relict geomorphic surfaces is the basic tool for establishing relative ages of the different surfaces. Landform elements are used to separate different geomorphic processes observed within a unit (e.g., nebkas, aeolian pans, and discontinuous patches of desert pavements). Landform elements are normally not represented in regional maps but mapped only at high-scale surveys.

Descriptions of the morphological soil profile and the sampling of the soil horizons were based on fifty-four soil pits following the criteria of Schoeneberger et al. (2002). Another seven soil pits were performed as soil control profiles (Fig. 2). The classification of the soils was according to the Soil Survey Staff (1999). Each soil sample was air-dried and screened (2 mm mesh size) to separate the gravel and estimate its percentage. In the finer earth fraction, the physical and chemical properties were determined using methods suggested by the US Salinity Laboratory Staff (1954), Page et al. (1982), and Klute (1986).

Sampling sites for vegetation types were selected through aerial photographs of scale 1:60,000. In each area of 2500 m<sup>2</sup> (50 m × 50 m), dominant communities and perennial species were registered. The abundance was estimated using the method proposed by Braun-Blanquet (1979).

## 2 Soil–Geomorphic Relationship: Origin and Pedogenic Features

The landscape in the study area is strongly expressed by a combination of the arid conditions, soil parent materials, and vegetation.

The fluvial process is the dominant geomorphic processes, although at present it is only manifested by the ephemeral action of the Arroyo La Turca and La Oriental (“arroyo” = creek) (Fig. 1). These two streams are tributaries of the Arroyo Perdido, located east and out of the study area.

In the surrounding area of the Cerro Solo ore deposits, the geomorphological units identified were: (1) Exhumed planation surfaces, (2) Pedisediment levels, (3) Pediment associations, (4) Alluvial fan relicts, (5) Modern alluvial fans, and (6) Alluvial plains and associated wetlands (*mallines*) (Fig. 2).

Geomorphic surfaces from pedisediment levels, pediment associations, alluvial fan relicts, and modern alluvial fans were distinguished (Fig. 2). Furthermore, small

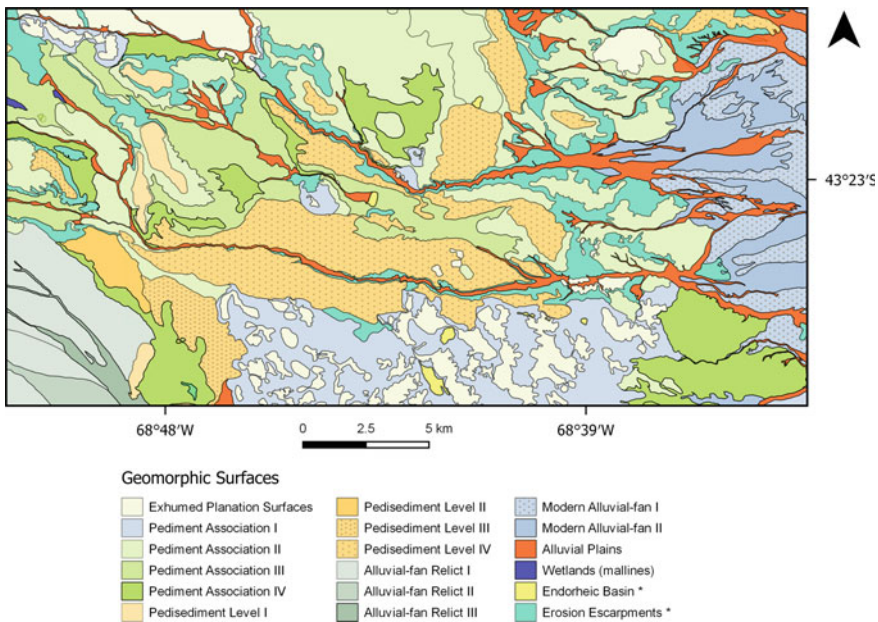


Fig. 2 Geomorphic surface of study area

endorheic basins and erosion escarpments were recognized in most geomorphological units. Geomorphic surfaces were identified by a Roman number according to the descending order of relative age on the basis of two relative age parameters: morphostratigraphic position and soil profile development.

The most important diagnostic horizons observed in Aridisols of the study area were: argillic, natric, calcic, petrocalcic, and gypsic. The physical and chemical properties of selected representative soil profiles are shown in Table 1.

Since the soil parent materials of the exhumed planation surfaces, pedisediment levels, alluvial fan relicts, and modern alluvial fans are free of carbonates and since the  $\text{Ca}^{2+}$  released during weathering is not adequate to explain the  $\text{CaCO}_3$  content in the soils, this mineral must have an allochthonous origin, mainly by aeolian influx. These carbonates were dissolved and redistributed in the soils by leaching water at determined depth where a new carbonate (pedogenic) was precipitated by evaporation (Fig. 3).

## 2.1 Exhumed Planation Surfaces

These landforms correspond to Gondwana paleosurfaces and is the result of deep chemical weathering and/or pedimentation processes, occurred in very stable tectonic environments and mostly under hypertropical climates, extremely wet, extremely arid, or seasonally changing (Rabassa et al. 2010, 2014).

In the study area, the exhumed planation surfaces are recognized by their rounded hills of mesosiliceous volcanic rocks from the Lonco Trapial Formation (Fig. 4a).

The soils are shallow with large amount of coarse and sharp rocky fragments. However, soils show signs of color changes and petrocalcic crusts between rock fragments. On the southern rocky outcrop, Calcic Lithic Petrocalcids occurred, with A-Bwk-2Bkm/R-R horizon sequence (profile 29; Fig. 4a). The vegetation is a shrub steppe community composed by *Nardophyllum obtusifolium*, *Nassauvia glomerulosa*, *Prosopis denudans*, *Lycium ameghinoi*, and *Atriplex lampa*.

On the other hand, in the northeastern part of the study area, Lithic Torriorthents were developed with an A-Bw/R-R horizon sequence (Profile 41; Fig. 4b). The vegetation is composed by a shrub steppe of *Mulguraea ligustrina*, *Senecio flaginoides*, *Mullinum spinosum* and *Nassauvia glomerulosa*.

## 2.2 Pedisediment Levels

A pedisediment is a sedimentary layer (alluvial deposit), eroded from the shoulder and back slope of an erosional slope that lies on and is, or was, being transported across a pediment (Peterson 1981). This geomorphological unit consists of at least

**Table 1** Soil properties of selected soil profiles

Horizons	Depth (cm)	Color (dry)	Structure <sup>a</sup>	Boundary <sup>a</sup> >2 mm (%)	Clay	Silt (%)	Sand (%)	EC <sup>b</sup> (dSm <sup>-1</sup> )	pH (1.2, 5)	CEC <sup>b</sup> (cmol/kg)	CaCO <sub>3</sub> (%)	SOM <sup>b</sup> (%)	Soluble salts (mmol/L)					ESP (%)				
													Na <sup>+</sup>	K <sup>+</sup>	Ca <sup>2+</sup>	Mg <sup>2+</sup>	Cl <sup>-</sup>		CO <sub>3</sub> <sup>2-</sup>	HCO <sub>3</sub> <sup>-</sup>	SO <sub>4</sub> <sup>2-</sup>	
Exhumed planation surfaces, Calcic Lithic Petrocalcids, profile 29																						
A	0-2	10YR 5/3	sg	ai	21	8.4	49.7	41.9	0.7	8.1	32.2	4.4	2.15	1.2	17.2	12.8	3.3	0.6	0.1	2.4	8.3	0
Bwk	2-25	7.5YR 5/6	sbk, m, 2	aw	15	23.1	49.1	27.8	0.4	8.6	40.9	15.8	1.68	1.0	4.6	8.0	1.0	0.2	0.0	1.6	6.5	0
2Bkm/R	25-44	7.5YR 8/2	pl, m, 3	ai	36	12.5	48.8	38.6	0.4	9.0	13.5	88.1	nd	2.0	1.9	4.9	1.4	0.3	0.2	1.4	6.4	0
2Ck/R	44-70	7.5YR 8/2	sg	ai	45	21.1	27.1	51.8	0.4	9.0	17.4	71.4	nd	2.0	3.1	4.1	2.0	0.2	0.1	1.3	5.7	0
R	>70	Rock fragments from LT F																				
Exhumed planation surfaces, Lithic Torriochents, profile 41																						
A	0-11	10YR 5/3	gr, m, 1	aw	48	26.5	30.8	42.8	0.4	7.5	48.3	1.3	1.84	2.1	0.3	5.5	3.3	0.3	0.0	1.2	4.1	0
Bw/R	11-38	7.5YR 5/6	sbk, m, 1	ai	70	16.0	33.3	50.7	0.3	7.4	58.3	1.6	nd	2.8	0.2	5.3	4.0	0.3	0.0	1.0	3.3	0
R	>38	Rock fragments from LT F																				
Pedisestment level I, Typic Haplocalcid profile 33																						
A1	0-6	10YR 6/3	sg	as	17	22.2	15.3	62.5	0.3	7.1	25.7	1.2	1.01	0.4	16.5	4.5	4.0	0.2	0.0	1.3	4.4	0
A2	6-24	10YR 4/4	sbk, m, 2	ai	9	21.7	28.1	50.2	0.3	8.1	39.1	1.8	0.70	0.5	6.9	4.3	1.6	0.2	0.0	1.0	2.7	0
Bt	24-40	10YR 5/4	sbk, m, 2	ai	9	27.9	21.6	50.5	0.3	8.3	43.5	1.9	0.69	0.4	5.4	4.0	2.6	0.3	0.0	0.9	2.6	0
2Ck1	40-64	10YR 7/4	sbk, f, 1	aw	31	18.5	13.5	68.1	0.3	8.5	30.4	21.7	nd	0.6	3.7	4.4	2.8	0.1	0.0	1.1	4.5	0
2Ck2	64-84	10YR 8/1	sg	as	38	11.9	11.6	76.6	0.3	8.9	26.1	30.9	nd	1.0	2.3	2.7	2.1	0.3	0.0	0.9	2.3	0
3Ck	>84	10YR 8/3	sg		24	10.6	5.9	83.6	0.3	8.9	23.0	19.9	nd	1.5	2.1	2.9	2.3	0.9	0.0	1.0	2.9	0
Pedisestment level IV, Typic Haplocalcid, profile 40																						
A	0-4	10YR 7/3	pl, f, m	as	33	16.9	20.5	62.6	1.3	8.1	25.7	2.2	0.67	0.4	0.5	24.9	9.6	0.2	0.0	1.1	22.3	0
Bk	4-35	10YR 5/3	sbk, m, 2	gw	25	17.6	19.8	62.7	0.4	8.5	28.3	4.1	0.53	0.5	0.1	7.4	1.4	0.3	0.0	1.1	4.5	0
C	35-63	10YR 6/3	sg	as	24	19.7	10.6	69.7	0.5	8.8	26.1	6.8	0.80	3.1	0.1	3.6	1.1	0.2	0.0	1.6	4.6	1
2Ck	63-89	10YR 8/3	sg	aw	32	21.4	2.9	75.7	0.7	9.2	23.9	29.2	0.38	4.9	0.1	2.5	0.5	0.2	0.0	2.0	6.5	3
3Bwtkb	89-140	7.5 YR 8/2	sbk, m, 2	gw	12	11.3	22.9	65.8	1.3	9.3	26.5	51.5	0.29	11.5	0.1	1.7	0.5	5.6	0.0	1.1	16.1	10
3Ck	>140	10YR 7/4	sg		43	6.9	25.3	67.8	7.0	8.1	29.1	12.7	nd	45.2	0.4	48.1	21.8	11.6	0.0	0.9	129.8	7

(continued)

Table 1 (continued)

Horizons	Depth (cm)	Color (dry)	Structure <sup>a</sup>	Boundary <sup>a</sup> >2 mm (%)	Clay	Silt (%)	Sand	EC <sup>b</sup> (dSm <sup>-1</sup> )	pH (1.2, 5)	CEC <sup>b</sup> (cmol/kg)	CaCO <sub>3</sub> (%)	SOM <sup>b</sup> Soluble salts (mmol/L)					ESP (%)																
												Na <sup>+</sup>	K <sup>+</sup>	Ca <sup>2+</sup>	Mg <sup>2+</sup>	Cl <sup>-</sup>	CO <sub>3</sub> <sup>2-</sup>	HCO <sub>3</sub> <sup>-</sup>	SO <sub>4</sub> <sup>2-</sup>														
Pediment level I, Typic Natrargids, profile 30																																	
Av	0-5	10YR 5/3	pl. f, 2	as	13	21.0	22.5	56.5	3.2	8.0	45.7	1.4	0.64	28.7	43.0	15.4	6.4	7.6	0.2	1.8	59.2	8											
Bm	5-23	5YR 4/6	gr. f, 2	gs	5	46.0	28.5	25.5	10.2	9.0	39.1	59.4	0.68	84.3	32.0	8.8	3.3	95.7	0.0	1.7	28.5	27											
Btkn	23-36	5YR 4/6	pr. m, 3	gs	2	61.4	17.7	20.9	9.9	9.1	39.1	21.7	0.39	82.6	26.0	8.0	4.3	84.1	0.0	1.2	33.5	27											
Ck1	36-48	5YR 4/4	m	aw	4	7.9	66.2	25.9	7.8	9.1	41.7	26.0	nd	73.0	22.0	6.3	2.0	57.7	0.0	1.1	29.5	28											
Ck2	>48	5YR 4/4	m		6	8.9	72.4	18.7	17.8	8.3	36.5	27.1	nd	144.3	28.0	51.1	14.4	87.3	0.0	0.9	114.7	21											
Pediment level II, Typic Torriorthents, profile 32																																	
A	0-7	7.5YR 5/4	sg	as	5	14.4	47.1	38.5	0.3	7.3	41.7	1.3	0.48	0.6	16.0	4.6	1.4	0.4	0.0	0.9	3.5	0											
Bwk	7-24	7.5YR 4/4	sbk. m, 2	as	2	36.9	28.5	34.6	0.3	8.0	51.3	4.1	0.86	0.9	3.5	4.5	1.7	0.1	0.0	1.1	4.0	0											
2Ck	>24	Green mudstones from CH G																															
Pediment level II, Typic Haplocalcids, profile 11																																	
A	0-8	7.5YR 8/5	pl. m, 1	aw	23	22	56	0.3	8.3	30.3	30.3	1.8	0.61	0.2	0.1	0.5	0.1	0.1	0.0	1.8	0.4	0											
Btk	8-21	7.5YR 6/4	sbk. c, 2	gw	5	27	30	44	0.4	8.3	40.7	10.9	0.65	0.5	0.0	0.9	0.1	1.3	0.0	2.5	0.3	0											
Bk	21-32	7.5YR 8/4	sbk. m, 2	aw	7	11	48	41	0.3	8.4	32.9	31.5	0.47	0.9	0.0	0.5	0.1	0.4	0.0	1.8	0.5	1											
Ck	>32	7.5YR 8/2	m		33	10	40	51	2.6	7.8	25.0	48.3	nd	1.3	0.0	1.9	0.2	0.4	0.0	0.5	4.0	0											
Pediment level III, Typic Natrargids, profile 31																																	
Av	0-4	10YR 6/3	pl. f, 2	as	21	24.1	21.7	54.3	1.3	8.1	15.2	1.4	0.58	10.4	12.0	3.9	4.8	3.7	0.1	2.2	14.3	5											
2Bt1	4-14	5YR 4/4	sbk. m, 3	gs	2	38.7	25.5	35.8	1.4	8.7	36.5	1.2	0.53	14.3	4.0	2.5	4.8	10.3	0.0	0.7	5.1	8											
2Bt2	14-27	5YR 5/6 (h)	sbk. f, 2	gs	3	44.6	37.4	18.0	4.8	8.8	15.2	5.7	1.00	36.5	7.0	9.8	3.3	40.1	0.0	1.1	6.9	13											
2Bkn	27-50	5YR 5/6	sbk. m, 2	as	3	10.4	63.5	26.2	7.0	9.0	62.6	9.8	0.34	61.7	10.0	12.6	7.3	52.7	0.0	1.4	39.8	18											
2Cky	>50	7.5YR 5/4	sbk. m, 1		5	10.2	70.9	18.9	12.1	8.2	53.9	6.5	nd	93.9	8.7	60.3	29.4	59.1	0.0	1.4	182.1	13											
Pediment level III, Typic haplrgids, profile 21																																	
A	0-7	10YR 5/4	sg	as	27	11	12	77	0.3	7.1	15.7	1.0	0.68	0.7	0.5	5.5	3.8	0.1	0.0	1.3	3.9	0											
C	7-20	10YR 5/4	sbk. m, 1	as	9	15	11	74	0.1	7.0	23.0	1.0	0.55	3.4	0.3	2.3	0.4	0.1	0.0	0.4	0.9	2											

(continued)



**Table 1** (continued)

Horizons	Depth (cm)	Color (dry)	Structure <sup>a</sup>	Boundary <sup>a</sup> >2 mm (%)	Clay Silt (%)	Sand EC <sup>b</sup> (dSm <sup>-1</sup> )	pH (1.2, 5)	CEC <sup>b</sup> (cmol/kg)	CaCO <sub>3</sub> (%)	SOM <sup>b</sup> Soluble salts					ESP (%)							
										Na <sup>+</sup>	K <sup>+</sup>	Ca <sup>2+</sup>	Mg <sup>2+</sup>	Cl <sup>-</sup>	CO <sub>3</sub> <sup>2-</sup>	HCO <sub>3</sub> <sup>-</sup>	SO <sub>4</sub> <sup>2-</sup>	ESP (%)				
2BU	20–36	7.5YR 5/4	sbk, m, 3	gs	4	30	10	60	0.2	7.0	38.6	1.0	0.41	0.9	0.1	2.1	2.0	0.1	0.0	0.6	1.9	0
2BU2	36–50	7.5YR 5/4	sbk, c, 2	gs	8	24	18	59	0.1	7.0	39.1	1.1	0.38	0.7	0.1	2.0	1.0	0.4	0.0	0.4	1.3	0
2C	50–70	10YR 5/4	m	aw	5	19	9	72	0.3	7.2	31.3	1.2	nd	1.0	0.1	5.4	2.4	0.1	0.0	1.4	2.9	0
3Ck	70–98	10YR 7/4	sg	as	23	14	0	86	0.2	8.6	17.7	2.4	nd	0.9	0.1	3.1	1.6	0.5	0.0	0.9	1.9	0
4C	>98	2.5Y 7/4	m		0	16	10	74	0.3	8.8	17.2	6.0	nd	1.3	0.1	4.9	2.5	0.2	0.0	1.3	5.0	0
Pediment level IV, Typic Torriorthents, profile 14																						
A1	0–13	7.5YR 6/4	gr, c, 1	aw	6	25	30	45	0.4	8.3	34.4	2.1	0.39	0.5	0.1	7.0	4.5	0.4	0.0	1.1	7.1	0
A2	13–31	7.5YR 6/4	sbk, m, 2	gw	11	23	28	49	0.4	8.3	35.0	3.3	0.47	0.7	0.1	5.6	3.4	0.2	0.1	1.2	8.3	0
2Bk	31–56	5YR 6/4	sbk, m, 3	gw	11	20	32	48	0.4	8.5	38.1	6.5	0.37	2.2	0.1	3.3	0.3	0.3	0.1	1.4	9.5	0
2Ck	>56	5YR 7/3	sg		7	23	21	56	1.4	8.8	35.0	6.3	nd	11.1	0.1	4.5	2.7	8.3	0.1	1.2	8.9	5
Pediment level IV, Lithic Torriorthents, profile 28																						
A	0–10	10YR 4/4	gr, f, 3	gs	36	16.2	16.5	67.3	0.2	7.0	15.2	1.2	0.80	0.6	25.5	2.2	1.9	0.1	0.1	0.4	3.8	0
2B/R	10–46	7.5YR 4/4	sbk, f, 3	ai	45	21.1	35.4	43.6	0.8	8.1	37.0	3.0	1.03	6.5	12.9	3.7	3.0	1.0	0.1	3.0	5.1	3
R	>46	Reddish sandstone	from Ch G																			
Alluvial fan relict I, Typic Haplocalcids, profile 22																						
A1	0–20	10YR 5/3	sbk, m, 3	gw	19	25	12	63	0.3	8.5	24.8	4.6	0.79	0.4	0.1	5.1	2.7	0.3	0.0	0.8	6.2	0
A2	20–37	10YR 5/4	sbk, m, 2	gw	21	17	20	63	0.3	8.6	23.0	7.3	0.90	0.5	0.1	6.1	1.9	0.1	0.0	0.8	6.5	0
2Bk1	37–61	10YR 7/4	m	as	34	17.6	13.2	69.2	0.4	8.7	23.0	16.5	nd	1.0	0.1	5.8	3.1	0.4	0.0	1.2	7.3	0
2Bk2	61–73	10YR 8/2	pl, m, f	as	59	15.4	7.4	77.2	0.4	8.8	22.2	28.2	nd	1.1	0.1	4.3	3.7	0.7	0.0	0.9	7.9	0
3Ck	>73	10YR 5/3	sg		20	12.7	0.0	88.9	0.3	9.1	15.2	8.9	nd	1.6	0.1	3.3	2.8	0.6	0.0	0.9	7.2	0
Alluvial fan relict II, Typic Haplocalcids, profile 25																						
A	0–22	10YR 4/4	sbk, m, 2	aw	12	28.8	23.5	47.7	0.3	8.2	21.3	1.0	0.71	0.6	0.4	3.6	2.7	0.1	0.0	0.9	5.0	0
C	22–43	10YR 4/6	sbk, m, 2	aw	46	10.8	28.5	60.7	0.3	8.6	25.2	1.0	0.50	0.7	0.4	3.5	3.0	0.2	0.0	1.2	4.1	0
2Bw	43–77	7.5YR 5/4	sbk, f, 2	aw	62	17.9	1.2	80.9	0.3	8.6	16.5	0.9	0.18	1.0	0.3	2.7	3.3	0.1	0.0	0.9	2.9	0

(continued)

**Table 1** (continued)

Horizons	Depth (cm)	Color (dry)	Structure <sup>a</sup>	Boundary <sup>a</sup> >2 mm (%)	Clay Silt (%)	Sand EC <sup>b</sup> (dSm <sup>-1</sup> )	pH (1.2, 5)	CEC <sup>b</sup> (cmol/kg)	CaCO <sub>3</sub> (%)	Soluble salts (mmol/L)					ESP (%)					
										Na <sup>+</sup>	K <sup>+</sup>	Ca <sup>2+</sup>	Mg <sup>2+</sup>	Cl <sup>-</sup>		CO <sub>3</sub> <sup>2-</sup>	HCO <sub>3</sub> <sup>-</sup>	SO <sub>4</sub> <sup>2-</sup>		
2C	77-96	7.5YR 5/6	sg	aw	65	10.8 3.2	86.0 0.3	8.7	8.7	1.1	1.5	0.2	2.3	2.0	0.1	0.0	1.0	3.4	0	
2Ck	96-120	7.5YR 8/2			60	14.0 0.0	86.0 0.4	9.1	11.7	15.8	3.7	0.2	3.5	3.0	0.1	0.0	1.5	7.4	1	
3C	>120	Sandy gravel deposits																		
Alluvial fan relict III, Typic Haplocalcids, profile 26																				
A1	0-5	10YR 4/4	sbk, m, 1	gs	33	16.8 25.0	58.2 0.3	7.9	22.6	1.4	0.82	0.3	0.5	6.2	1.7	0.1	0.0	1.2	5.1	0
A2	5-27	10YR 5/4	sbk, m, 2	gw	26	13.1 33.6	53.3 0.4	8.5	25.7	1.5	0.49	0.3	0.1	7.0	3.4	0.2	0.1	1.2	8.4	0
Ck	27-44	10YR 5/4	sg	ai	36	8.2 21.1	70.7 0.4	8.5	23.0	6.2	nd	0.3	0.1	9.3	3.4	0.5	0.0	1.4	12.0	0
2Bk(m)	44-135	10YR 8/2	sgs, pl, m, 3	as	36	14.0 11.7	74.3 0.3	8.7	17.4	41.1	nd	0.9	0.0	5.6	3.6	0.6	0.1	1.2	5.6	0
3C	>135	10YR 5/3	sg		12	5.1 2.4	92.5 0.6	9.8	11.3	3.2	nd	4.7	0.0	1.5	0.8	0.1	0.0	1.7	6.3	4
Modern alluvial fan I, Typic Natrargids, profile 44																				
AV	0-4	10YR 7/3	pl, f, 3	aw	13	28.9 15.7	55.5 3.5	8.8	18.3	1.2	0.54	33.5	0.6	7.5	3.4	30.2	0.7	1.6	5.6	13
2Btm	4-11	7.5YR 4/4	sbk, f, 3	aw	2	39.5 14.8	45.7 5.8	8.8	36.1	1.3	0.25	50.4	0.6	7.4	2.9	52.7	0.0	0.8	3.0	19
2Bkn1	11-21	7.5YR 5/4	sbk, m, 3	as	4	41.3 16.8	41.9 9.6	9.0	45.2	7.0	0.57	84.3	0.5	11.0	4.7	86.5	0.0	1.3	29.7	25
2Bkn2	21-43	7.5YR 5/6	sbk, m, 2	gs	28	7.0 53.1	39.9 8.4	9.2	70.4	19.0	0.77	84.3	0.5	7.9	4.0	69.7	0.0	1.5	40.6	28
2Ck	43-92	7.5YR 5/4	sg	as	22	10.0 5.5	84.5 13.2	9.0	25.2	8.1	nd	121.7	0.5	48.9	22.0	48.4	0.0	0.8	169.3	18
3Ck	>92	7.5YR 7/4	m		4	11.9 4.8	83.4 8.2	9.5	12.2	5.6	nd	80.0	0.5	8.7	4.8	49.2	0.0	1.1	76.6	25
Modern alluvial fan I, Typic Haplargids, profile 6																				
A	0-11	10YR 7/2	pl, f, 2	as	14	19 16	65 0.4	8.4	21.7	0.7	0.45	2.0	0.1	0.4	0.2	0.3	0.0	2.6	0.4	3
2Bt	11-26	7.5YR 4/4	pr, f, 3	as	7	33 28	38 0.4	8.7	41.3	1.3	0.45	2.7	0.0	0.2	0.1	0.5	0.0	2.1	0.5	6
2Btk	26-44	7.5YR 5/4	sbk, m, 3	gs	24	10 17	73 0.5	9.0	31.7	4.2	0.28	3.1	0.1	0.2	0.1	0.9	0.0	2.4	0.9	7
2Ck	44-76	7.5YR 6/2	sg	as	37	8 1	91 0.5	9.2	19.6	3.9	nd	4.1	0.0	0.2	0.0	1.2	0.0	2.9	0.6	11
3Ck	76-100	7.5YR 6/4	sbk, m, 1	as	8	5 10	84 2.0	9.5	19.6	1.3	nd	30.4	0.1	0.8	0.3	29.2	0.0	3.4	2.8	31
4Ck	>100 (150)	7.5YR 6/4	sg		10	7 5	88 3.0	9.3	17.4	4.2	nd	24.0	0.0	0.7	0.3	25.9	0.0	1.2	2.4	27

(continued)

**Table 1** (continued)

Horizons	Depth (cm)	Color (dry)	Structure <sup>a</sup>	Boundary <sup>a</sup> >2 mm (%)	Clay	Silt (%)	Sand	EC <sup>b</sup> (dSm <sup>-1</sup> ) (1,2,5)	pH	CEC <sup>b</sup> (cmol/kg)	CaCO <sub>3</sub> (%)	SOM <sup>b</sup> Soluble salts (mmol/L)					ESP (%)												
												Na <sup>+</sup>	K <sup>+</sup>	Ca <sup>2+</sup>	Mg <sup>2+</sup>	Cl <sup>-</sup>		CO <sub>3</sub> <sup>2-</sup>	HCO <sub>3</sub> <sup>-</sup>	SO <sub>4</sub> <sup>2-</sup>									
Modern alluvial fan II, Typic Torriorthents, profile 7																													
A	0–19	10YR 5/3	pl. c, 1	as	16	17	69	0.2	7.9	23.5	0.9	0.26	0.6	0.2	0.4	0.1	0.1	0.0	1.7	0.2	0								
C	19–42	10YR 6/3	sg	ai	16	16	70	0.2	7.8	24.3	0.8	0.29	0.8	0.1	0.4	0.1	2.4	0.1	1.5	0.3	1								
2Ck1	42–92	10YR 6/4	sg	aw	22	8	89	0.3	9.4	17.8	7.6	nd	2.5	0.0	0.1	0.0	0.1	0.0	2.1	0.2	9								
2Ck2	92–142	10YR 6/4	sg	as	13	6	93	0.2	9.8	16.5	5.0	nd	3.7	0.0	0.1	0.0	0.5	0.0	3.0	0.6	11								
3Bkb	>142	7.5YR 7/4	sbk, m, 1		17	7	88	0.7	9.8	21.3	7.6	nd	7.6	0.0	0.2	0.0	3.0	0.0	2.7	1.2	19								
Modern alluvial fan II, Sodic Haplocalcids, profile 5																													
A	0–11	10YR 5/3	pl. c, 1	as	14	8	79	12	8.2	22.2	0.9	0.30	0.6	0.2	0.4	0.1	0.2	0.0	1.7	0.3	0								
C	11–45	10YR 6/4	sbk, m, 1	aw	14	10	75	0.4	8.4	29.6	0.6	0.25	1.3	0.0	0.4	0.1	0.9	0.0	1.9	0.4	1								
2Bk	45–125	7.5YR 6/4	sbk, c, 1	aw	6	4	93	5.0	8.5	27.8	30.3	0.17	41.5	0.0	5.2	1.8	4.6	0.0	1.0	28.8	19								
2Ck	125–165	7.5YR 6/4	sg	as	12	3	41	5.6	8.2	26.1	10.4	nd	53.9	0.0	5.3	2.1	14.0	0.0	0.8	34.5	23								
3Bkb	>165 (190)	7.5YR 6/4	sbk, m, 3		1	9	49	4.2	8.0	37.4	15.9	nd	62.3	0.1	5.5	2.3	34.4	0.0	0.8	31.2	26								
Alluvial plains, Typic Torriorthents, profile 37																													
A	0–4	5YR 6/4	pl. f, 3	aw	0	35.0	36.8	28.3	0.7	8.4	51.3	3.5	1.65	2.0	0.8	10.0	6.5	0.3	0.0	2.9	4.7	0							
C	4–21	7.5YR 6/4	sbk, m, 2	as	1	25.0	23.2	51.9	1.2	8.7	33.0	1.6	0.45	6.1	0.6	11.8	2.3	2.2	0.0	0.9	3.3	1							
2Ck	21–80	7.5YR 6/4	sbk, c, 1	as	4	26.1	17.7	56.3	0.5	9.3	36.5	9.2	nd	5.7	0.2	1.9	0.7	0.2	0.0	1.8	4.5	4							
R	>80	Reddish sandstone from Ch G																											
Alluvial plains, Typic Torriorthents, profile 18																													
A1	0–18	10YR 6/4	pl. m, 1	as	14	28	29	43	0.4	8.0	30.3	2.1	0.63	0.3	0.6	5.7	1.9	0.3	0.0	1.1	1.8	0							
A2	18–28	10YR 6/4	sbk, m, 2	aw	12	29	25	46	0.4	8.4	34.4	1.7	0.56	0.8	0.7	2.1	0.9	0.7	0.0	1.0	1.9	0							
Ck1	28–75	5YR 6/4	sg	aw	23	25	23	52	0.4	8.9	28.7	8.5	0.49	1.8	0.1	3.6	2.1	0.1	0.0	1.5	4.3	0							
Ck2	>75	5YR 6/4	sg		23	18	27	55	0.6	9.3	26.1	6.4	nd	4.8	0.1	1.9	0.8	0.5	0.0	1.6	6.8	3							

(continued)

Table 1 (continued)

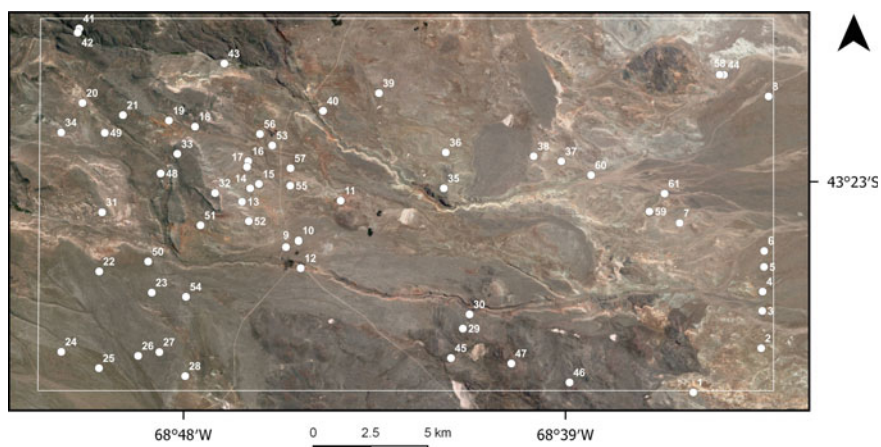
Horizons (cm)	Color (dry)	Structure <sup>a</sup>	Boundary <sup>a</sup> >2 mm (%)	Clay Silt (%)	Sand EC <sup>b</sup> (dSm <sup>-1</sup> )	pH (1.2, 5)	CEC <sup>b</sup> (cmol/kg)	CaCO <sub>3</sub> (%)	SOM <sup>b</sup> (%)	Soluble salts (mmol/L)					ESP (%)						
										Na <sup>+</sup>	K <sup>+</sup>	Ca <sup>2+</sup>	Mg <sup>2+</sup>	Cl <sup>-</sup>		CO <sub>3</sub> <sup>2-</sup>	HCO <sub>3</sub> <sup>-</sup>	SO <sub>4</sub> <sup>2-</sup>			
Wetlands (mallines), Aquic Torrifluvents, profile 43																					
A	0-22	10YR 3/3 m	as	0	50.8	31.7	17.5	4.8	8.7	62.6	8.6	2.12	44.3	1.2	13.3	19.4	9.3	0.0	5.1	74.5	11
C1	22-41	7.5 YR 4/4 gr, f, 2	as	0	25.7	55.3	19.9	5.1	8.7	48.7	6.5	1.03	43.9	1.2	14.7	32.6	13.1	0.0	2.4	83.3	9
C2	41-61	10YR 3/3 m	as	0	18.0	66.7	15.3	3.3	8.8	48.7	11.9	nd	29.6	0.6	9.7	21.3	8.4	0.0	2.0	56.7	8
C3	>61 WT	Water table																			
Wetlands (mallines), Aquic Haplocalcids, profile 20																					
A	0-22	10YR 6/3 sbk, c, 3	as	1	27	36	37	4.5	9.2	40.7	14.4	1.39	49.6	0.6	7.4	9.3	36.3	0.0	2.4	71.5	17
Bwk	22-30	10YR 7/3 sbk, m, 2	aw	0	13	50	37	1.1	9.3	45.4	12.7	0.53	16.5	0.1	1.5	3.5	3.4	0.0	1.4	17.5	11
2Ab	30-40	10YR 6/2 sbk, m, 1	aw	3	13	37	50	0.8	9.1	38.6	8.6	0.39	7.1	0.1	2.0	1.9	1.8	0.1	1.4	13.4	5
2Bwkb	40-50	5 YR 6/4 sbk, m, 2	gw	7	22	44	34	0.8	9.4	41.7	10.1	0.22	7.4	0.1	2.6	3.0	0.9	0.0	1.2	4.5	4
2Bklb	50-75	10YR 7/2 sbk, m, 2	gs	0	22	24	54	0.8	9.5	28.2	21.3	0.20	6.4	0.1	1.3	2.4	1.1	0.0	0.9	11.9	5
2Bk2b	>75	10YR 7/3 sbk, m, 2		16	15	23	62	1.0	9.6	24.5	21.1	0.18	9.3	0.1	1.7	2.3	1.5	0.0	1.3	9.2	6

Roman numerals indicate chronosequence levels (geomorphic surfaces)

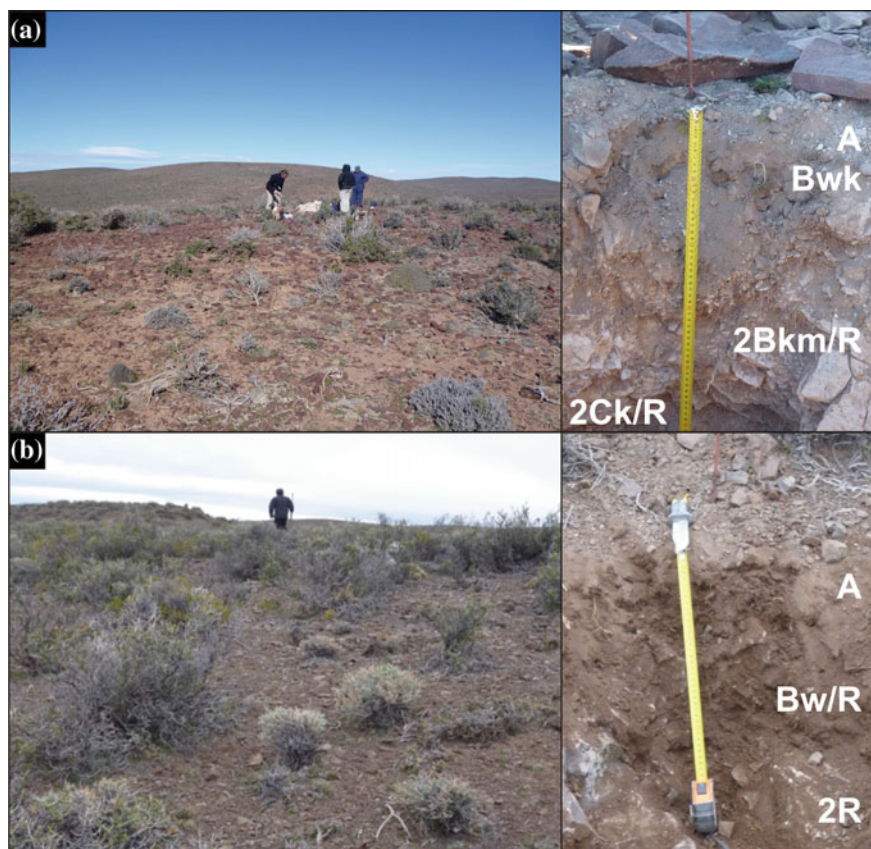
LTF Lonco Triapial Formation; Ch G, Chubut Group

<sup>a</sup>Abbreviations for morphological description are from Schoeneberger et al. (2002); structure: gr granular, sg single grain, m massive, pl platy, pr prismatic, sbk subangular Blocky, size: vf very fine, f fine, m medium; grade: 1 weak, 2 moderated, 3 strong; boundary, distinctness: a abrupt, g gradual; topography: w wavy, s smooth, i irregular

<sup>b</sup>Soil properties: EC electrical conductivity; SOC soil organic carbon; ESP exchangeable sodium percentage; CEC cation exchange capacity



**Fig. 3** Location of soil profiles



**Fig. 4** Exhumation planation surface, Lonco Trapial Formation; **a** Calcic Lithic Petrocalcids (profile 29); **b** Lithic Torriorthents (profile 41)

four levels of relict pedisediment (geomorphic surfaces between 830–570 m a.s.l.; Figure 5). The slope of pedisediments is planar with a slight tilt to the east and southeast (1–1.5%). These deposits correspond to the Renguenao Formation and are composed of sandy gravel sediments (1–6 m) deposited on pediments carved on continental sedimentary rocks of the Chubut Group. Rhyolites and andesites are the main component of the gravel size fraction, and in smaller proportion basalts. In the coarse fraction (>2 mm), fragments of mudstone and calcitic concretions from the Chubut Group were also observed.

The soils of the pedisediment levels were classified as Typic Haplocalcids. The soils of pedisediment I have an A1-A2-Bt-2Ck1-2Ck3-3Ck horizon sequence (e.g., profile 33; Fig. 5a). Although clay coatings were observed in the subangular blocks, the amount of illuvial clay is not enough to define an argillic horizon.

In general, the pedisediment levels I–III are observed as isolated relicts in the northwest of the study area, between 850 and 750 m a.s.l. Vegetation communities

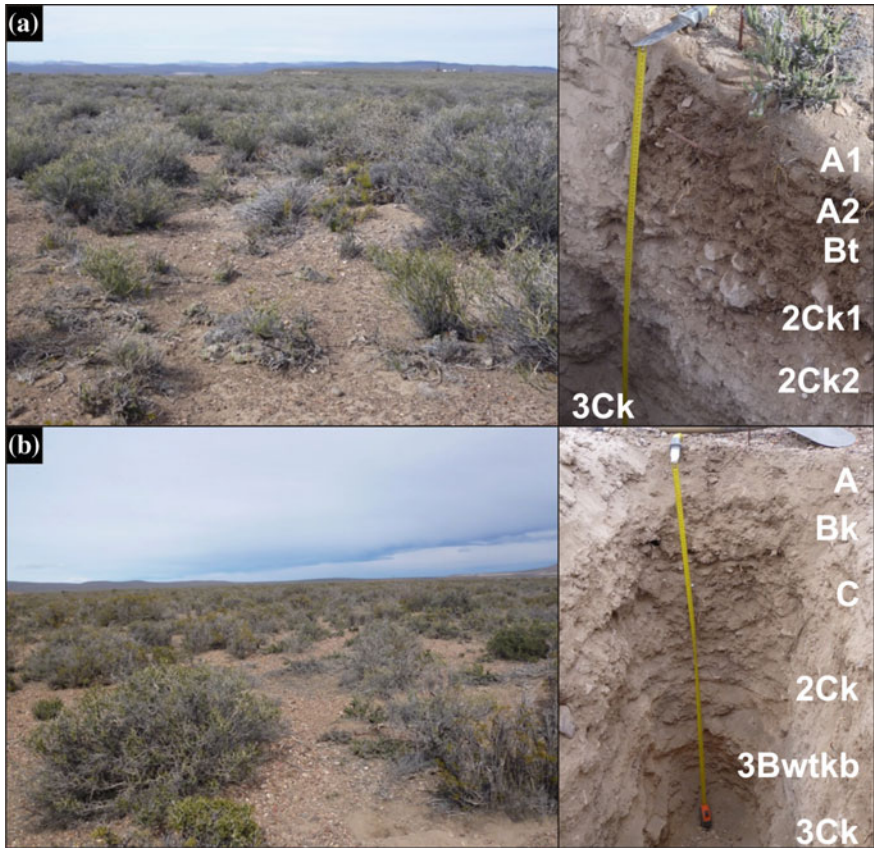


Fig. 5 Pedisediment levels, Typic Haplocalcids; a level I (profile 33); b level IV (profile 10)

(35% cover) are considered shrub steppe composed by *Mulguraea ligustrina*, *Nardophyllum obtusifolium*, and *Nassauvia glomerulosa*.

The Pedisediment level IV covers a greater area and it is distributed between 730 and 560 m a.s.l. mainly along the La Turca creek. In profile 10, pedogenic gypsum nodules occur at depth (>180 cm), indicating a *per descensum* origin of the soil solutions. In profile 40, a pinkish-buried paleosol is observed at 90 cm in depth with clay coatings between subangular blocks of 3Bwtkb horizon (Fig. 5b). Vegetation (20% cover) of this geomorphic surface is a shrub steppe composed by *Ephedra ochreatea*, *Mulguraea ligustrina*, *Chuquiraga avellanadae*, and *Nardophyllum obtusifolium*.

### 2.3 Pediment Associations

A pediment is defined by a gently and short slope transport surfaces of bedrock, covered by a thin alluvium, developed between an upland area where erosion dominates (i.e., the erosion scarps) and a lower plain where active aggradation dominates (i.e., *Bajadas* or Coalescent alluvial fans). Dohrenwend and Parsons (2009) defined this sequence of landforms and processes on hillslope as a pediment association.

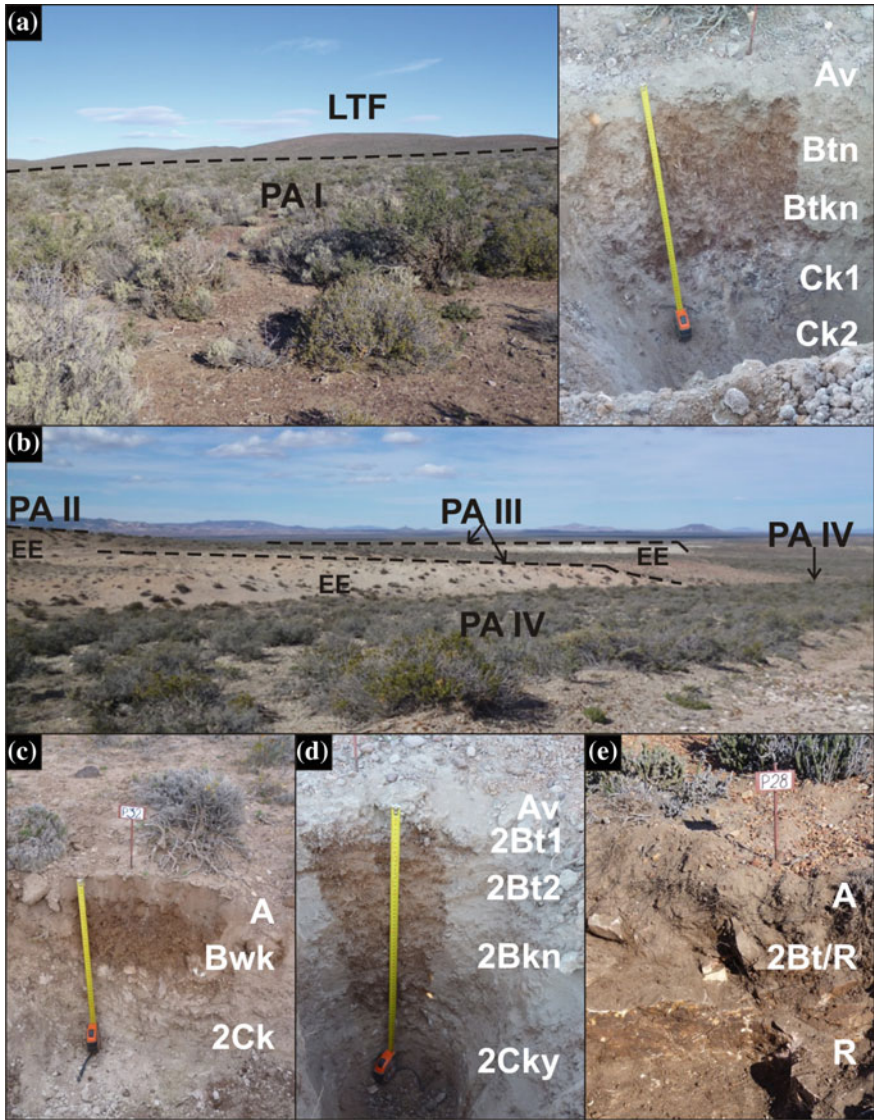
In the study area, this geomorphological unit corresponds to an erosional landscape of the Chubut Group. This unit is highly dissected, recognizing at least four levels of pediments caused by local changes in base level (Fig. 6a, b).

The parent materials are composed of varied sedimentological facies (mudstone, sandstone) of the Cerro Barcino Formation (Chubut Group) and a thin colluvial layer of the same material re-transported.

However, whereas all geomorphic surfaces have similarities in their parent materials significant differences in their morphological, physical and chemical properties are clearly observed (Table 1). This variety of soil types is depending on the age of geomorphic surface and the degree of polygenesis, this last resulting from the alternation of morphogenesis periods with pedogenic periods.

The pediment level I is confined between the rounded hills of the exhumed planation surface (Fig. 6a). The soils have a certain pedological evolution with natric horizons formation. The general horizon sequence is Av-2B<sub>tn</sub>-2B<sub>tkn</sub>-2C<sub>k1</sub>-2C<sub>k2</sub> and the soils were classified as Typic Natrargids (e.g., profile 30) with a shrub steppe vegetation community (30% cover) composed of *Atriplex lampa*, *Chuquiraga avellanadae*, and *Nassauvia ulicina*. In inter-shrubs spaces, the natric horizon (2B<sub>tn</sub>-2B<sub>tkn</sub>) is exhumed by raindrop impact and surface water runoff erosion where vesicular horizons and desert pavements are developing at the surface.

The soils of pediment level II have lithological discontinuities that indicated erosion–deposition processes with A-2B<sub>wk</sub>-2C<sub>k1</sub>-2C<sub>k2</sub> (e.g., profile 32; Fig. 6c) or A-B<sub>tk</sub>-B<sub>k</sub>-C<sub>k</sub> (e.g., profile 11) horizon sequences, where the soils were classified as Typic Torriorthents and Typic Haplocalcids, respectively. The vegetation of Torriorthents (20% cover) is predominantly shrub steppe and sub-shrubby steppe



**Fig. 6** Pediment associations; **a** PA I Pediment Association I, Typic Natrargids (profile 30), LTF Lonco Trapial Formation; **b** PA II–IV Pediment association levels; EE erosion scarp (Chubut Group); **c** PA II, Typic Torriorthents (profile 32); **d** PA III, Typic Natrargids (profile 31); **e** PA IV, Lithic Torriorthents (profile 28)



dominated by: *Chuquiraga avellanadae*, *Nardophyllum obtusifolium*, *Mulguraea ligustrina*, and *Prosopis denudans*, whereas in Haplocalcids, the vegetation (30% cover) is a sub-shrubby steppe with isolated shrubs dominated by *Nassauvia glomerulosa* and *Franquenina sp.*

The pediment level III occupies an area larger than pediment level II, and the soils show prominent argilic horizons (Bt1-Bt2; Bt-Btk) with greater degree of development (Table 1). The soils were classified as Typic Natrargids (e.g., profile 31; Fig. 6d) and Typic Haplargids (profile 21). The vegetation of pediment level III (25% cover) is predominantly shrub steppe dominated by: *Chuquiraga avellanadae*, *Prosopis denudans*, *Jarava speciosa*, *Lycium ameghinoi*, and *Nassauvia sp.*

The soil morphology of the profiles may differ in the degree of evolution and erosion or burial. The surface horizons may vary from thin layers vesicular (Av), A horizons or A-C horizon sequences that overlie argilic horizons.

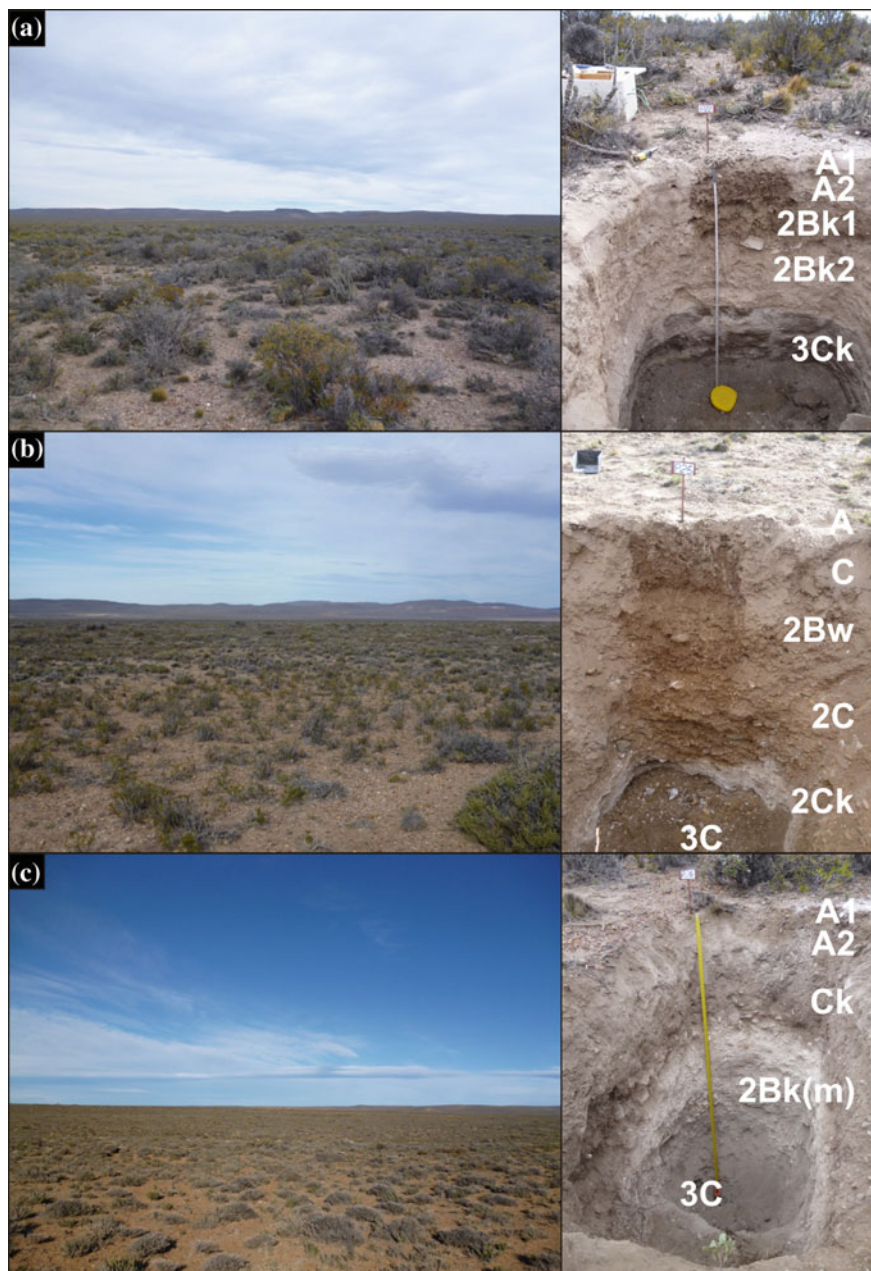
The pediment level IV is more associated with erosion scarps of sedimentary rocks of the Chubut Group. This is observed mainly in the headwaters of the La Turca and La Oriental creeks. The soils have a weak development, where the soil parent material is exposed or covered by a thin alluvial–colluvial deposit (covered pediment). The soil profile is simple; the partially pedogenized Cretaceous sedimentary rocks are covered by alluvial–colluvial parent materials (A1-A2, A-C, or A-C1-C2-C3 horizons). According to the occurrence and depth (<50 cm) of the lithic contact, the soils were classified as Typic Torriorthents (profile 14) and Lithic Torriorthents (profile 28; Fig. 6e). The vegetation associated with these soils (25% cover) is predominantly shrub steppe and sub-shrubby steppe dominated by *Nardophyllum obtusifolium*, *Nassauvia glomerulosa*, *Prosopis denudans*, and *Lycium ameghinoi*.

## 2.4 Alluvial fan Relicts

This geomorphological unit is composed of three levels of relict alluvial fans (geomorphic surfaces) situated to the southwest of the study area on the eastern piedmont slope of the Sierra de Pichiñán.

Typic Haplocalcids are the soil types derived from these geomorphic surfaces. However, whereas their parent materials are gravel and sand deposits, free of carbonates, gypsum and soluble salts, important differences in their morphological, physical, and chemical properties are neatly observed (Table 1).

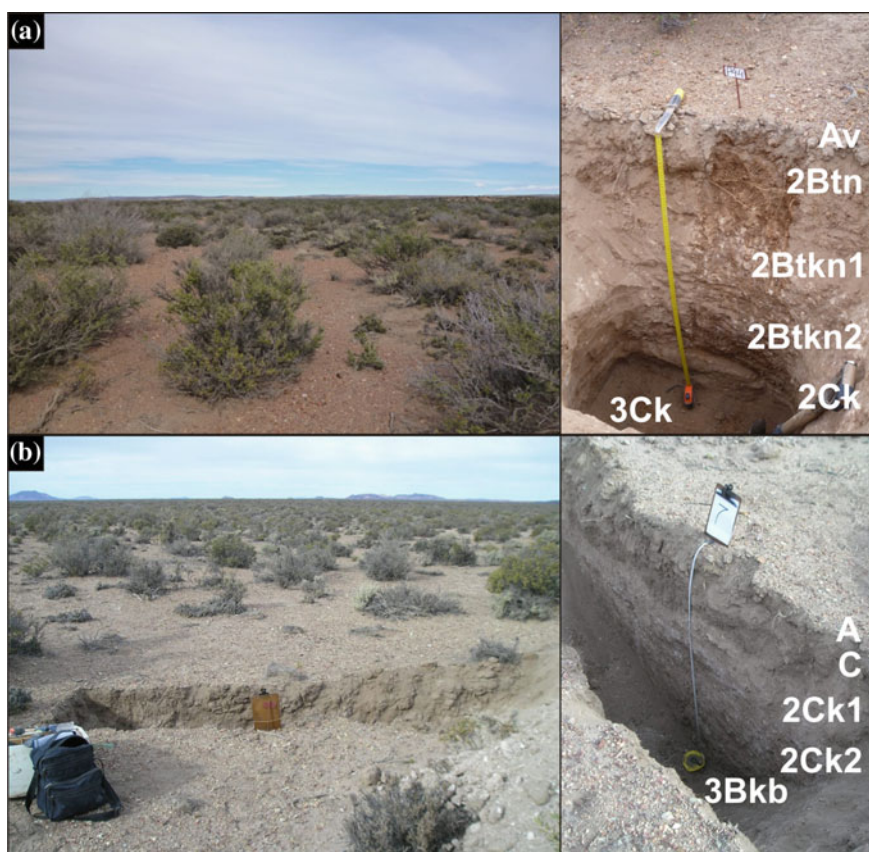
The soils of alluvial fan relict I (Fig. 7a) have sandy loam and loamy sand surface horizons (A1-A2 or A-C horizons) that lies on calcic (2Bk1-2Bk2 horizons; e.g., profile 22). Their vegetation is a shrub steppe composed by *Nassauvia glomerulosa*, *Nassauvia axilaris*, *Colliguaja integerrima*, and *Nardophyllum obtusifolium*.



**Fig. 7** Alluvial fan relicts, Typic Haplocalcids; **a** Alluvial fan relict I (profile 22); **b** Alluvial fan relict II (profile 25); **c** Alluvial fan relict III (profile 26)

The soils of alluvial fan relict II geomorphic surface (Fig. 7b, profile 25) have less pedogenic carbonate content than soils of Alluvial fan I, and present a color change at discontinuity from dark yellowish brown (10 YR 4/6; A-C horizons) to brown and strong brown (7.5YR 5/4, 5/6; 2Bw-2C-2Ck horizons). The vegetation of alluvial fan II is a sub-shrubby steppe dominated by *Grindelia chilensis*, *Maihuenia patagonica*, *Colliguaja integerrima*, and *Ephedra ochreatea*.

Alluvial fan relict III (Fig. 7c) is an erosional geomorphic surface that is superimposed at the alluvial fan I. The soil profile described on pit 26 shows this relation; the A1-A2-C horizons bury the 2Bk-3C horizons; this last sequence of horizon corresponds to the soil of alluvial fan I. In 2Bk horizon, petrocalcic crust fragments were observed, presumably incorporated from older geomorphic surfaces with petrocalcic horizons.



**Fig. 8** Modern alluvial fans; **a** Modern alluvial fan I, Typic Natrargids (profile 44); **b** Modern alluvial fan II, Typic Torriorthents (profile 7)

## 2.5 Modern Alluvial fans

This geomorphological unit (Fig. 8) is located east of the study area and is formed by sedimentary accumulations from the La Turca and La Orientalia creeks.

The soil parent materials are alluvial deposits composed by the finer fraction of soil (<2 mm) and gravels from Cretaceous fragments of mudstones and sandstones of the Chubut Group.

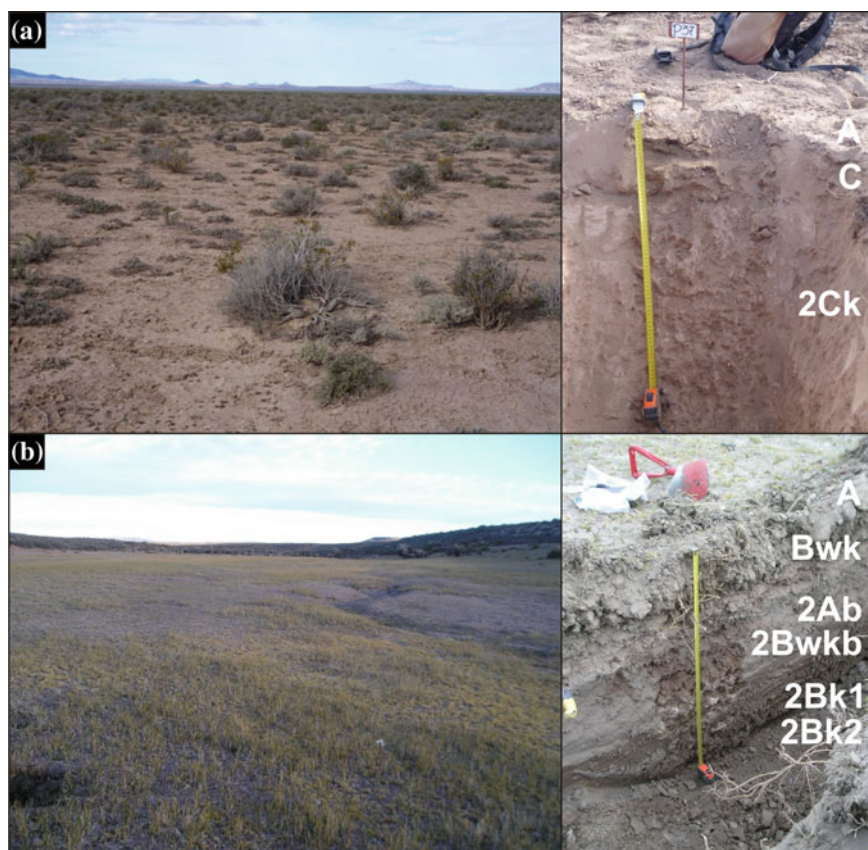
In this unit, two modern alluvial fans were distinguished; modern alluvial fan I has soils with certain pedologic evolution as Typic Natrargids (e.g., profile 44; Fig. 8a) and Typic Haplargids (e.g., profile 6). The vegetation of this geomorphic surface is a shrubby steppe (20% cover) dominated by *Lycium ameghinoi*, *Chuquiraga avellanadae*, *Atriplex lampa*, and *Nassauvia ulicina*. Modern alluvial fan II buries the modern alluvial fan I. The soils were classified as Sodic Haplocalcids (profile 5) in the distal fan and Typic Torriorthents (profile 7; Fig. 8b) in the proximal fan. In both profiles, a 3Bkb horizon at 150 cm in depth is correlated with 2Bk horizons of soils from the modern alluvial fan I. The vegetation of Modern alluvial fan II surface is a shrubby steppe (30% cover) dominated by *Lycium ameghinoi*, *Chuquiraga avellanadae*, *Atriplex lampa* and *Nassauvia ulicina* and *Prosopis denudans*.

## 2.6 Alluvial Plains and Associated Wetlands (Mallines)

This geomorphological unit corresponds to the active alluvial plains of the La Turca and La Orientalia creeks, tributary streams and the *bajadas* of endorheic basins.

Soils are poorly developed, and its parent materials are composed of alluvial deposits of fine particle size (<2 mm and fine gravels) that are overlying reddish sedimentary rocks of the Chubut Group. The soils were classified as Typic Torrifluvents (e.g., profile 37; Fig. 9a) accompanied by Typic Torriorthents (e.g., profile 18). The vegetation of alluvial plains is a shrubby steppe (20% cover) composed by *Junellia tridactilis*, *Lycium ameghinoi*, *Chuquiraga avellanadae*, and *Prosopis denudans*.

Wetlands, locally named *mallines*, are located in restrained areas of the La Turca and La Orientalia creeks with underground water discharge at the thalweg sectors of the channels. The soils have water table and horizons with redox depletions (chroma  $\leq 2$ ) within 100 cm of the soil surface, and thus, the soils were classified as Aquic Torrifluvents (e.g., profile 43) and Aquic Haplocalcids (profile 20; Fig. 9b). The vegetation of wetlands is a grass steppe (50% cover) dominated by *Juncos sp.*, *Dystichlis sp.*, and *Carex banksii*.



**Fig. 9** a Active Alluvial plains, Typical Torrifluvents (profile 39); b wetlands (“mallines”), Aquic Haplocalcids (profile 20)

### 3 Perspectives and Future Work

From the preceding paragraphs, it is concluded that the study of geomorphology–soil relationship is not only a tool to correlate unconsolidated deposits, but also to characterize the pedological contents and vegetation communities associated with the geomorphological units and geomorphic surfaces. Also, this information could be used to determine the productivity indexes (or soil-quality index) at landscape scales (Schaeztl et al. 2012), for instance, the different geomorphic surfaces.

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